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CHANDRA reveals galaxy cluster with the most massive nearby cooling core, RXCJ1504.1-0248

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ABSTRACT

A CHANDRA follow-up observation of an X-ray luminous galaxy cluster with a compact appearance, RXCJ1504.1-0248 discovered in our REFLEX Cluster Survey, reveals an object with one of the most prominent cluster cooling cores. A β-model fit to the X-ray surface brightness profile gives a core radius of $\sim 30 h_{70}^{-1}$ kpc which is much smaller than the cooling radius with ~ 140 kpc. As a consequence more than 70% of the high X-ray luminosity of $L_{bol} = 4.3\ 10^{45} h_{70}^{-1}$ erg s^{-1} of this cluster is radiated inside the cooling radius. A simple modeling of the X-ray morphology of the cluster leads to a formal mass deposition rate within the classical cooling flow model of $1500 - 1900$ M$_\odot$ yr^{-1} (for $h_{100} = 0.7$, and $2300 - 3000$ M$_\odot$ yr^{-1} for $h_{100} = 0.5$).

The center of the cluster is marked by a giant elliptical galaxy which is also a known radio source. Thus it is very likely that we observe one of the interaction systems where the central cluster AGN is heating the cooling core region in a self-regulated way to prevent a massive cooling of the gas, similar to several such cases studied in detail in more nearby clusters. The interest raised by this system is then due to the high power recycled in RXCJ1504-0248 over cooling time scales which is about one order of magnitude higher than what occurs in the studied, nearby cooling core clusters. The assumption that cooling is exactly balanced by the AGN heating implies a central black hole mass growth rate of the order of 0.5 M$_\odot$ yr^{-1}. This cluster is therefore a prime target for the study of AGN-intracluster medium interaction at very extreme conditions. Further features common to cooling cores found in this cluster are a strong temperature drop towards the center and narrow, low ionization emission lines in the central cluster galaxy.

The cluster is also found to be very massive, with a global X-ray temperature of about 10.5 keV and a total mass of about $1.7\ 10^{15} h_{70}^{-1}$ M$_\odot$ inside $3 h_{70}^{-1}$ Mpc.

Subject headings: galaxies: clusters: general, galaxies: cooling flows, galaxies: clusters: individual: RXCJ1504.1-0248, X-rays: galaxies: clusters

1. Introduction

One of the currently most debated questions concerning the structure of the X-ray luminous, hot intracluster plasma of clusters of galaxies is the consequence of the small cooling time of this plasma in those clusters with dense central cores (e.g. Fabian 1994). XMM-Newton X-ray spectroscopy has shown that in spite of its short cooling time the gas is not cooling at the high expected rates in the absence of heating processes (e.g. Peterson 2001, 2003; Matsushita et al. 2002; Böhringer et al. 2002; Molendi 2002). The most popular scenario which allows for a self-regulated heating of the hot plasma in cluster cooling cores and prevents massive cooling is the heating of the intracluster medium (ICM) by the jets and radio lobes of the AGN in the central cluster galaxies (e.g. Churazov et al. 2000, 2001; McNamara et al. 2000; David et al. 2001; Fabian 2003; Forman et al. 2004). It was shown that this interaction provides enough power in many nearby cooling flows to at least balance cooling. For example the current kinetic energy output of the inner radio lobes in M87 in Virgo and NGC 1275 in the Perseus cluster is with estimated values of $\sim 10^{44}$ erg s^{-1} and $\sim 10^{45}$ erg s^{-1}, respectively, in both these cases about an order of magnitude higher than the cooling power in the cooling core (Churazov et al. 2000, 2003; Birzan et al. 2004). Recently further very deep and detailed X-ray observations have given some insight into the details of the heating process, which is proposed to occur through the dissipation of sound waves set off by the interaction of the radio lobes with the ICM (Fabian 2003) or by shock fronts (Forman et al. 2004, Nulsen et al. 2005a, 2005b, McNamara et al. 2005). A promising picture seems to be emerging where the recycling of AGN energy with powers in the order of 10^{44} to 10^{45} erg s^{-1} in cluster cooling cores of nearby clusters could explain the observed phenomena.

Searching through larger volumes of our Universe, more extreme cases of cluster cooling cores can be found, where the rate of AGN energy recycling is even higher by up to an order of magnitude. The cluster with the largest cooling core detected so far, RXCJ1347.5-1144 at z=0.4516 was discovered in the REFLEX survey (Schindler et al. 1995; Böhringer et al. 2004a) with a formally derived cooling flow mass deposition rate of the order of 3000 $M_\odot$ yr^{-1} (for a Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1}; Schindler et al. 1997; Allen 2000) which corresponds to an energy dissipation of $\sim 10^{46}$ erg s^{-1}. This cluster is unfortunately much more distant than the well studied nearby clusters and does not lend itself easily to a detailed observational study. We have now discovered a more nearby, similarly striking massive cooling core cluster in the REFLEX Survey, RXCJ1504.1-0248 at a redshift of $z = 0.2153$. This cluster was flagged as a cluster candidate due to a galaxy overdensity detected in the COSMOS data base (McGillivray & Stobie 1984) and six concordant galaxy redshifts found in our subsequent follow-up observations confirmed the existence of a cluster. Three of these cluster galaxies show AGN-like spectra.

Serious doubts remained about the cluster identification of this X-ray emitter, because the X-ray source appeared much too compact for its high luminosity, compared to the other clusters in the REFLEX sample in the same distance and luminosity range. This could possibly be attributed to a contaminating central AGN. The certain identification clearly required a higher resolution X-ray observation, which could recently be made through a CHANDRA snap-shot exposure yielding a perfect cluster image without significant contamination by point sources (Fig.1). With these source properties it becomes immediately clear that RXCJ1504.1-0248 must have an extremely bright core and is potentially a very interesting cooling core cluster.

In this paper we study the structure of this cluster in more detail. In section 2 and 3 we present the observational results. Section 4 is devoted to the modeling of the mass profile and the determination of the parameters in the frame of a classical cooling flow model. In section 5 we discuss further phenomenological features related to the cooling core of the cluster and section 6 provides the conclusion. We will adopt a cosmological model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s^{-1} Mpc^{-1}, except if it is noted otherwise. Thus 1 arcmin at the distance of RXCJ1504-0248 corresponds to 209 kpc.

2. Observation and Data preparation

RXCJ1504.1-0248 was observed with the CHANDRA ACIS-I on January 7, 2004 for 13463 sec. The observation was hardly disturbed by times of high background and the net exposure after standard cleaning procedures is 13 298 sec. Fig. 2 shows an image of the cluster in the 0.5 - 2 keV energy band superposed on an optical R-band image taken as 5 min exposure in our REFLEX redshift survey at the ESO La Silla 3.6m telescope. The total ACIS-I count rate in the region $r \leq 6$ arcmin in the 0.5 to 2 kev band is 2.03 cts s^{-1} implying an unabsorbed flux of about 1.18 and $1.9 \cdot 10^{-11}$ erg s^{-1} cm^{-2} in the $0.5 - 2$ kev and $0.1 - 2.4$ keV energy bands, respectively. In the ROSAT All-Sky Survey we found a flux of $2.2(\pm 0.11) \cdot 10^{-11}$ erg s^{-1} cm^{-2} in the $0.1 - 2.4$ keV band within an aperture of 12 arcmin radius, in reasonable agreement with the new results from the much deeper image.

The X-ray cluster center coincides well with a central dominant galaxy that can be identified with LCRS B150131.5-023636 at the J2000 position 15 04 07.5 -02 48 16 at z=0.216917 (Shechtman et al. 1996). The optical image of the cluster and the spectrum of the galaxy B150131.5-023636 described in section 5 have been obtained with EFOSC2 at the 3.6m telescope of ESO La Silla on Aug. 14 and 20, 2001, respectively.

3. Analysis and Results

The above noted fluxes imply an X-ray luminosity of $L_x = 2.3 \cdot 10^{45} h_{70}^{-1}$ erg s^{-1} in the $0.1 - 2.4$ keV band and a bolometric X-ray luminosity of $L_x = 4.3 \cdot 10^{45} h_{70}^{-1}$ erg s^{-1}. This makes this cluster the most prominent X-ray luminous cluster in the southern sky at redshifts below $z = 0.34$, with only two galaxy clusters at larger distances in the REFLEX catalogue having a higher X-ray luminosity. The X-ray image in Fig. 1 shows a high degree of regularity with a slightly elliptical shape and a major axis approximately along a position angle of about 40 degrees (North to East). As seen in Fig. 2 the center of the X-ray emission is marked by a dominant giant galaxy in the optical.

The azimuthally averaged X-ray surface brightness profile from which the background was subtracted is well described by a β-model out to a radius of about 300 arcsec, outside which the background subtraction uncertainties become significant (Fig. 3). The background was estimated either from the outer region of the CCD or from an external background field. Remarkable is the small core radius of $r_c \sim 30\ h_{70}^{-1}$ kpc and the high central gas density of $n_{e0} \sim 0.16 h_{70}^{1/2}$ cm^{-3}. The slope parameter, β, has the very typical value of 0.6.

The temperature profile was determined by fitting a spectral MEKAL model with fixed galactic absorption with a column density of 6 10^{20} cm^{-2} (as measured from 21 cm observations, Dickey & Lockman 1990) to the spectra obtained from the photons extracted from concentric rings around the cluster center. The background for subtraction was taken either from a background region at the outer parts of the detector (radial zone 3.8 to 5.7 arcmin) or from a background field in the same rings as taken for the target spectral extraction. Since there is some faint X-ray emission from the cluster almost throughout the entire detector, the on-target background subtraction prevents an accurate temperature determination at larger radii. Fig 4 provides a comparison of both methods, showing that the two approaches yield practically identical results out to a radius of 1 arcmin, but the analysis based on an external background field can be extended to a radius of 3 arcmin. While the bulk temperature of the cluster is about 10.5 keV, we note a strong temperature drop towards the center to a value below 5 keV. Such a temperature drop by a factor of 2 or 3 is observed in many cooling core clusters (e.g. De Grandi & Molendi 2002; Fabian 2003; Ikebe et al. 2004; Sanders et al. 2004). A possible temperature drop to larger radii indicated by the data cannot be established with the present photon statistics. Fig. 5 shows the spectrum of the innermost circle (0 - 15 arcsec). For the given photon statistics the spectrum is well fit by a one-temperature MEKAL model. We do not note any features which could indicate the Fe L line complex observed at lower temperatures, which would indicate the presence of cooler temperature phases.

In Fig. 4 we show 3 rough fits of analytic expressions to the temperature profile which

were chosen to approximately bracket the inner and outer gradients of the temperature profile. The analytical expressions are:

$$T_1(\mathrm{keV}) = 3.5 + 0.44 \cdot r^{0.9} - 0.044 \cdot r^{1.4} + 0.0007 \cdot r^2 \text{ (for } r < 150)$$

$$\text{and } T_1 = 11.076 - 0.00544 \cdot r \text{ (for } r > 150)$$

$$T_2(\mathrm{keV}) = 3.0 + 0.305 \cdot r^{0.9} - 0.0192 \cdot r^{1.4} \text{ (for } r < 100)$$

$$\text{and } T_2 = 9.80 + 0.003322 \cdot r \text{ (for } r > 100)$$

$$T_3(\mathrm{keV}) = 3.5 + 0.52 \cdot r^{0.9} - 0.0526 \cdot r^{1.4} + 0.00083 \cdot r^2 \text{ (for } r < 150)$$

$$\text{and } T_3 = 12.932 - 0.01364 \cdot r \text{ (for } r > 150)$$

where the radius, r, is in units of arcsec.

The spectral fits also indicate abundances of heavy elements (dominated by the fit to the Fe K line) of about 0.3 to 0.4 solar with large errors of about 0.1 to 0.2 in solar units (abundances based on Anders & Grevesse 1989). To our surprise we do not find a strong increase of the iron abundance towards the center, as seen in many cooling flow clusters (DeGrandi & Molendi 2001), but a deeper observation is necessary to draw a firm conclusion.

4. Modeling the cluster structure

4.1. Mass profile

From an analytical deprojection of the β-model fit to the X-ray surface brightness profile of the cluster and the temperature profile we can obtain the cluster mass profile under the assumption of hydrostatic equilibrium and spherical symmetry. The resulting mass profile is shown in Fig. 6 together with the profile of the gas mass, as derived from the β-model fit. For the gravitational mass profile we also indicate the typical uncertainties determined from the local minima and maxima of the mass profile for the different analytical temperature fits shown in Fig. 4. An additional scaling uncertainty of 15% for T_1 and T_2 and 5% for T_3 is included. At a radius of 3 h_{70}^{-1} Mpc the total mass is 1.8(+0.35, −0.28) 10^{15} h_{70}^{-1} $M_\odot$. For the radius $r_{200} = 2.3$ Mpc we find a mass of 1.5 10^{15} h_{70}^{-1} $M_\odot$. Thus RXCJ1504-0248 is among the most massive clusters known. The gas-to-total mass ratio for the two fiducial radii is 0.17(+0.03, −0.07) and 0.15(+0.03, −0.05), respectively.

4.2. Cooling flow analysis

To gain an understanding of the processes occuring in the central ICM of this cluster we start with a classical cooling flow analysis (e.g. Fabian et al. 1984; Thomas et al. 1987). We take two approaches. For the more simple model A we equate the energy loss by radiation inside a given radius, r, with the enthalpy influx from outside through the sphere with radius r. In model B we formulate the energy balance in a local differential way and include the gain of gravitational energy of the material flowing in from the outer regions.

$$\dot{M}(r) = 4\pi r^2 \frac{n_e^2 \Lambda(T) + \frac{\dot{M}(r+\Delta r)}{\Delta r 4\pi r^2} \cdot \frac{5k_B T}{2\mu m_p}}{\frac{5k_B}{2\mu m_p}\left(\frac{T}{\Delta r} + \frac{dT}{dr}\right) + \frac{M(r)G}{r} + \frac{\Phi}{\Delta r}}$$

where $\Lambda(T)$ is the cooling function normalized to the electron density squared, Δr is the shell width in the numerical calculation, Φ is the gravitational potential, and the other symbols have their usual meaning.

Fig. 7 shows the cooling time as a function of the cluster radius. If we take the often used fiducial value of 10^{10} years, we find a cooling radius of 140($\pm$5) kpc (for a Hubble constant of $h_{100} = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.7$) and 165($\pm$5) kpc (for $h_{100} = 0.5$). Here the uncertainty is determined from the minima and maxima for the different adopted fits to the temperature profile. Fig. 8 then shows the mass flow rates determined for model A and B and the cooling radius is indicated by vertical lines. For this adopted cooling radius we find mass flow rates of 1400 and 1900 $M_\odot$ yr^{-1} (for $h_{100} = 0.7$) and 2300 and 2930 (for $h_{100} = 0.5$) for model B and A, respectively.

These high formal cooling flow mass deposition rates make RXCJ1504-0248 the most prominent cooling flow cluster next to the most luminous cluster known, RXCJ1347-1144 at $z = 0.45$ for which also a mass deposition rate of the order of 3000 $M_\odot$ yr^{-1} (for $h_{100} = 0.5$) was deduced (Schindler et al. 1997; Allen 2000). This makes RXCJ1504-0248 a very interesting target to study the cooling core phenomenon under the most extreme conditions.

5. Discussion

In the new scenario of the physics of cooling core clusters, the large radiative cooling rates are compensated by the energy released from a central AGN (e.g. Churazov et al. 2000, 2001; McNamara et al. 2000; David et al. 2001; Böhringer et al. 2002; Fabian 2003; Forman et al. 2004). To keep the balance such that neither massive mass condensation nor a dispersion of the dense gaseous core occurs, the heating has to be fine-tuned. This is

achieved by a self-regulation system where large mass deposition rates in the center lead to an increased feedback from the AGN which limits the cooling rate. Seen from the perspective of the central AGN, its accretion rate is limited by the amount of cooling that can occur, that is the energy that can be dissipated by the ICM in the cooling core region (Churazov et al. 2002). In this cooling core scenario a high radiative power of the central ICM indicates a fast accretion of the interacting AGN.

The case of RXCJ1504-0248 is an extreme case in this scenario. Since the core radius is so small, actually much smaller than the cooling radius by a factor of about four, the major part of the total X-ray luminosity (about 72%) originates from inside the cooling radius. This corresponds to a total radiation power of $\sim 3\ 10^{45}$ erg s^{-1}. So far we have no direct indication that this cooling rate is balanced by AGN heating in this system. Some support for this scenario is discussed below. Assuming that the above sketched cooling core scenario applies and that the observed cooling power inside the cooling radius is balanced by the energy output from the AGN we can calculate further interesting system parameters. If the radiation power is replenished by accretion power from the AGN and if we assume an energy return efficiency, $\eta = 0.1$ from accretion onto the AGN black hole we can imply an accretion rate of the order of 0.5 M$_\odot$ yr^{-1}. Thus, in this mode the central black hole can gain a considerable mass of the order of the most massive black holes known over cosmic times.

Therefore it is very interesting to see if this scenario actually applies to RXCJ1504-0248. So far the observational evidence is far less detailed as for the best observed nearby cooling core clusters and the implications indicated above remain very speculative. But the few additional features known, point in the right direction. The central dominant galaxy is known to harbor a radio source with a brightness of 62 mJy at 1.4 GHz (Bauer et al. 2000) and thus it presumably contains a massive black hole. The radio source image obtained from the NVSS survey is, however, unresolved and featureless. A zoom into the central region of the CHANDRA image (Fig. 9) shows indications of an asymmetric distortion which could be due to the interaction of the AGN jets with the intracluster medium. Better photon statistics is needed to draw a more firm conclusion. Therefore deeper X-ray observations have been scheduled for CHANDRA and a detailed VLA radio study has been proposed for this cluster.

The central dominant galaxy is extremely large. The Gunn r magnitude of 16.4 determined in the Las Campanas redshift survey (Shechtman et al. 1996) translates into an absolute magnitude of $M_r \sim -24$ which corresponds to about 3×10^{11} L$_\odot$ in this band. It places this galaxy in the upper few percent of the luminosity distribution of cluster central galaxies as found for example by comparison to the survey by Lauer and Postman (1994).

The optical spectrum of the central galaxy, shown in Fig. 10, shows narrow, low excitation emission lines, notably strong [O II], weaker [O III], and bright Hα/[NII] lines, similar to what has been observed for many massive cooling flows (e.g. Hu, Cowie & Wang 1985; Johnstone, Fabian & Nulsen 1987, Heckman et al. 1989, Donahue, Stocke & Gioia 1989; McNamara & O'Connell 1993; Crawford et al. 1999). This provides another hint that this cluster resembles a scaled-up version of the known nearby cooling core clusters.

A very similar spectrum has been observed and studied in detail in the central galaxy of the cooling core galaxy cluster A2597 by Voit & Donahue (1997). In the spectrum of A2597 the [OII] line is even more dominant compared to the other lines. Voit & Donahue provide a very comprehensive discussion on the origin of this spectrum. They conclude that hot stars constitute the best fitting source of ionization, but to match the spectral properties with an photoionization nebular model an additional heat source has to be assumed which may well be the heating source of the cooling core. The same discussion most probably applies also to this object, but to perform the same analysis a deeper spectroscopic observation is required to get accurate line fluxes for more diagnostic lines. Very similar spectra can also be found among the spectra compiled from central cluster galaxies by Crawford et al. (1999). It is very striking that the spectra which best match the spectrum of RXCJ1504-0248 are those from the prominent well known cooling flow clusters, such as Z3146, A1835, A2204, and A2390. Overall these spectra show some variation in the degree of ionization with [OII] and [OI] lines being more prominent compared to [OIII] in Z3146 and [OIII] being relatively more prominent in A2390 than in the present case. But the close resemblance is very obvious. Within the classification scheme of AGN the present observation features as a LINER spectrum.

The equivalent width of the [OII] line is about 151 ± 2.43 Å corresponding to a line flux of about 9×10^{-14} erg s^{-1} cm^{-2}. Together with the total luminosity of the galaxy and the relation of [OII] luminosity and star formation rate as given by Kennicutt (1992) we get formally a star formation rate of the order of about 50 M$_\odot$ yr^{-1}. This is not untypical for a massive cooling core cluster (e.g. McNamara 1997). Since there are surely other ionization sources present, this simple modeling is certainly an oversimplification.

6. Conclusion

The CHANDRA observation reveals the X-ray source RXCJ1504-0248 as a galaxy cluster that has extreme and surprising properties in two respects. It is found to be a very massive cluster and the most luminous cluster known in the southern sky at redshifts lower than $z \leq 0.3$. Secondly, the cluster appears extremely compact with a very dense central

region. Thus the high X-ray luminosity is the result of both, the large cluster mass and the high central density.

These properties would make the cluster a cooling flow with one of the largest mass deposition rates ever inferred. But the observation of a radio AGN in the cluster center and the absence of low temperature signatures in the central X-ray spectrum leads us to suspect that the dense central ICM region is heated by the AGN like it is implied from the X-ray observations for nearby clusters. The heating source required in RXCJ1504-0248 needs to have a power about an order of magnitude larger than that of the nearby well studied cooling core clusters. This extreme energy recycling will surely make RXCJ1504-0248 a very interesting study object for many future investigations. This X-ray source has been accepted for observations with ASTRO-E2 which should for example provide insight into the degree of turbulence prevailing in the cooling core region.

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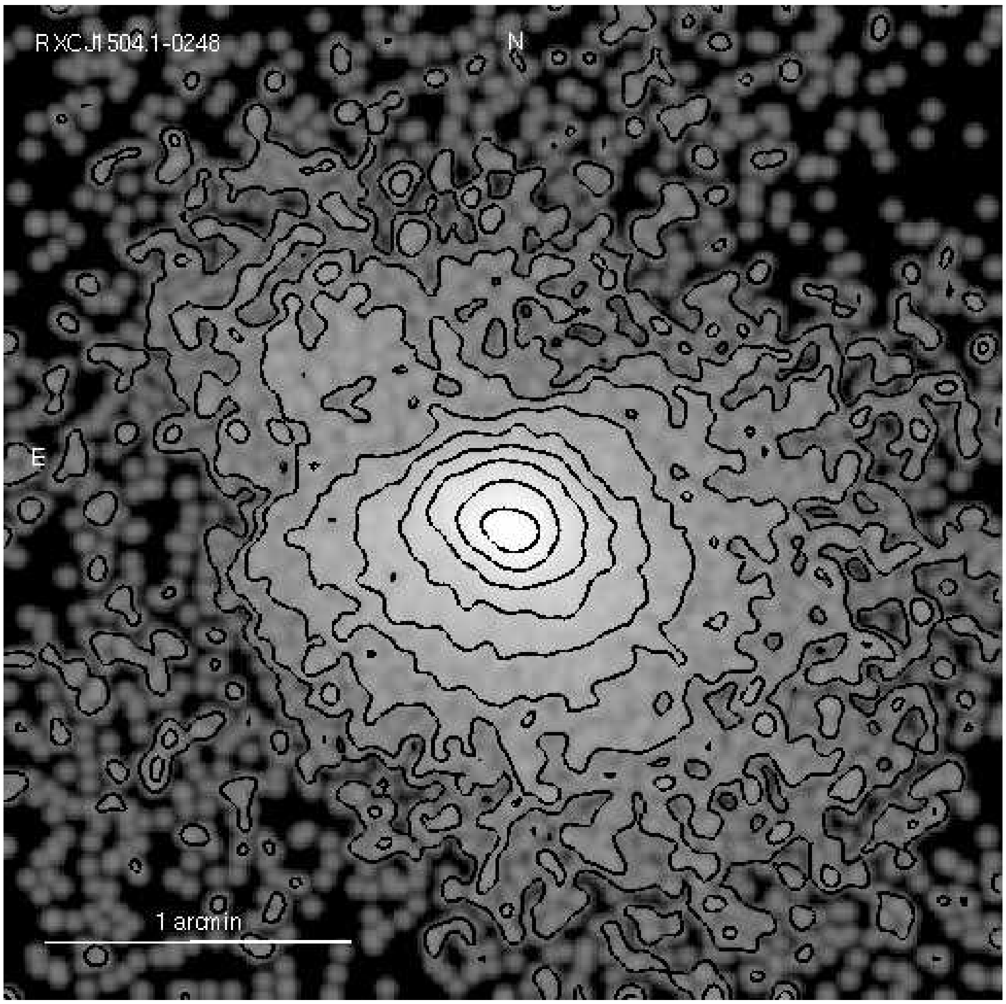

Fig. 1.— CHANDRA ACIS I image of RXCJ1504.1-0248 in the 0.5 to 2 keV band. The contour levels increase by factors of two. The sharp surface brightness drop north of the cluster center with a position angle $PA \sim 115\,\mathrm{deg}$ is an artefact produced by the gaps in the ACIS I CCDs. North is up and East is left.

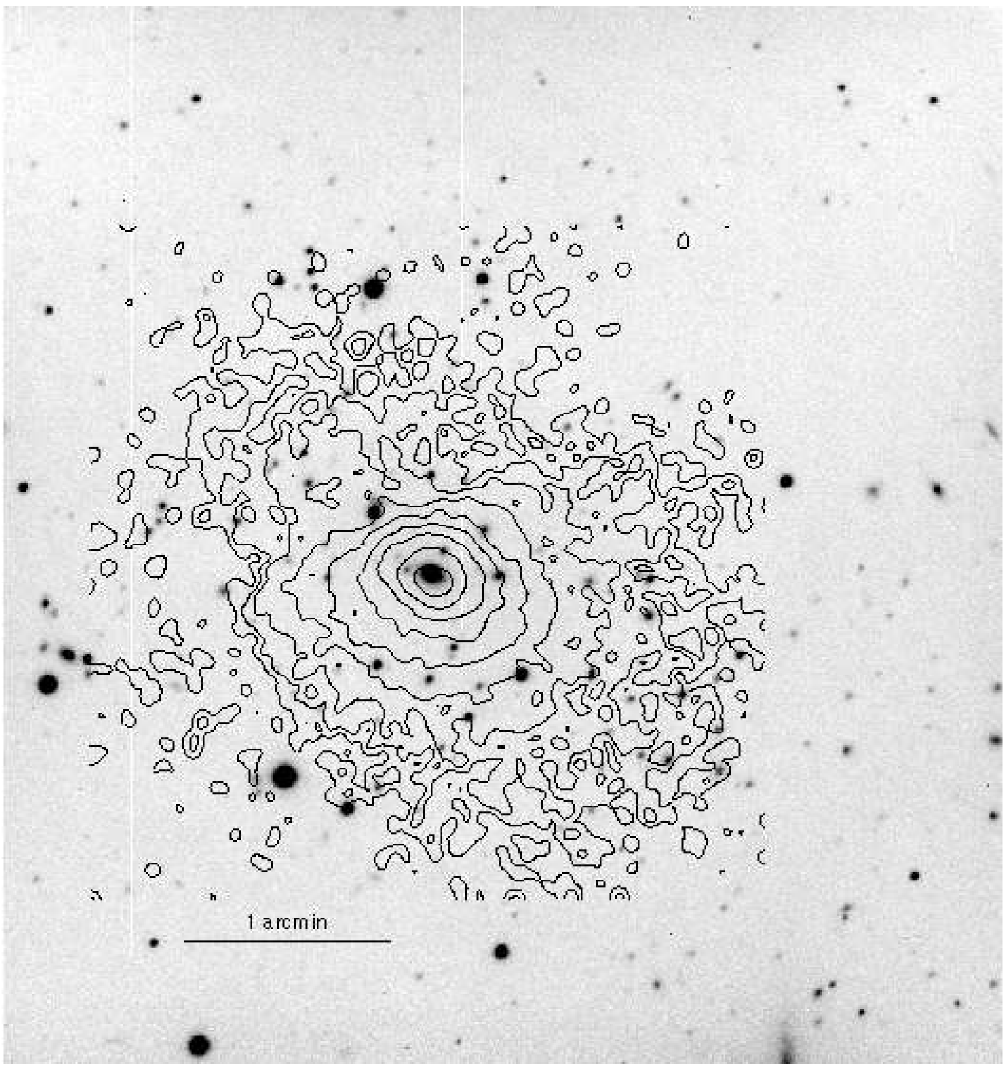

Fig. 2.— R-band image of the cluster RXCJ1504.1-0248 taken at the 3.6m ESO telescope overlayed with the X-ray contours of Fig. 1. North is up and East is left.

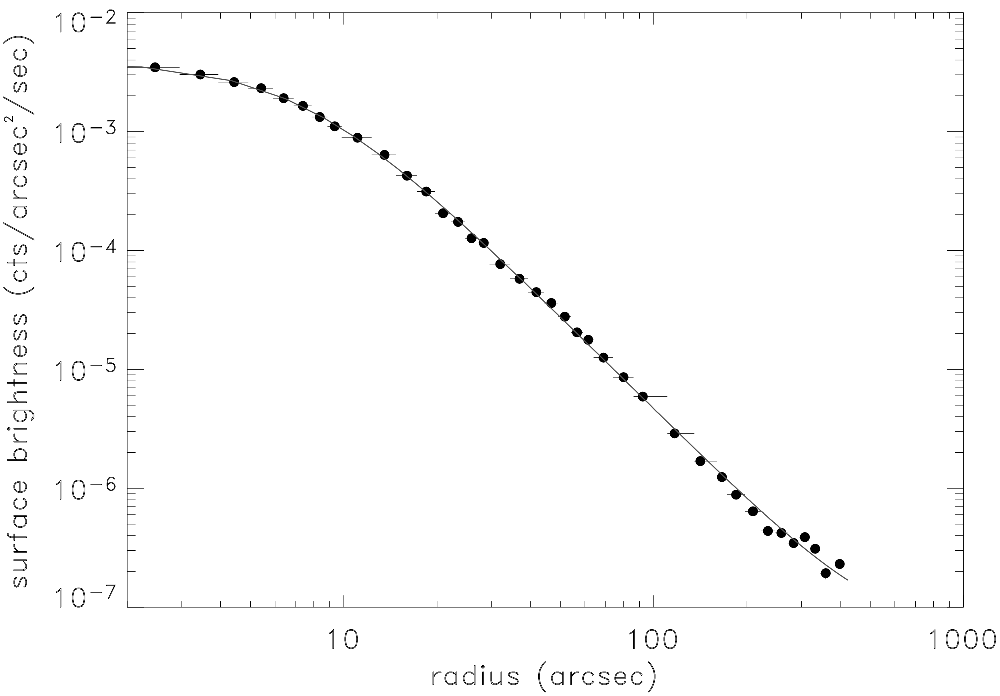

Fig. 3.— Surface brightness profile of RXCJ1504.1-0248 in the 0.5 to 2 keV band fit by a β-model.

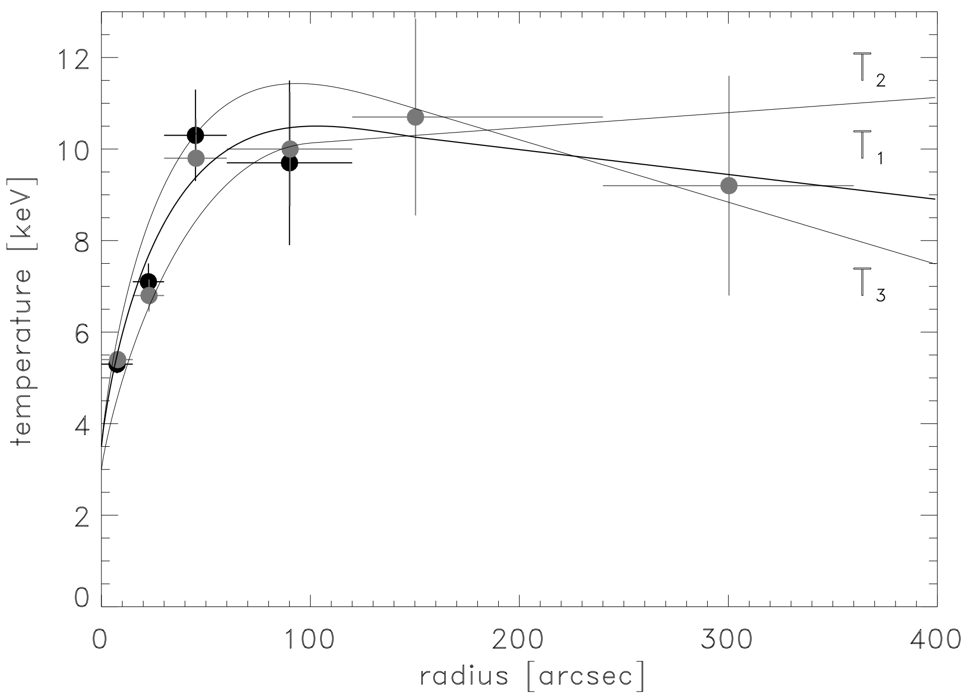

Fig. 4.— Temperature profile of RXCJ1504.1-0248 determined from the spectroscopic analysis of the ACIS I data in four concentric rings. The black dots show the temperature determination with the on-target background while the grey dots show the results of the spectral analysis using the background field. The lines show the three analytic representations of the temperature profile described in the text.

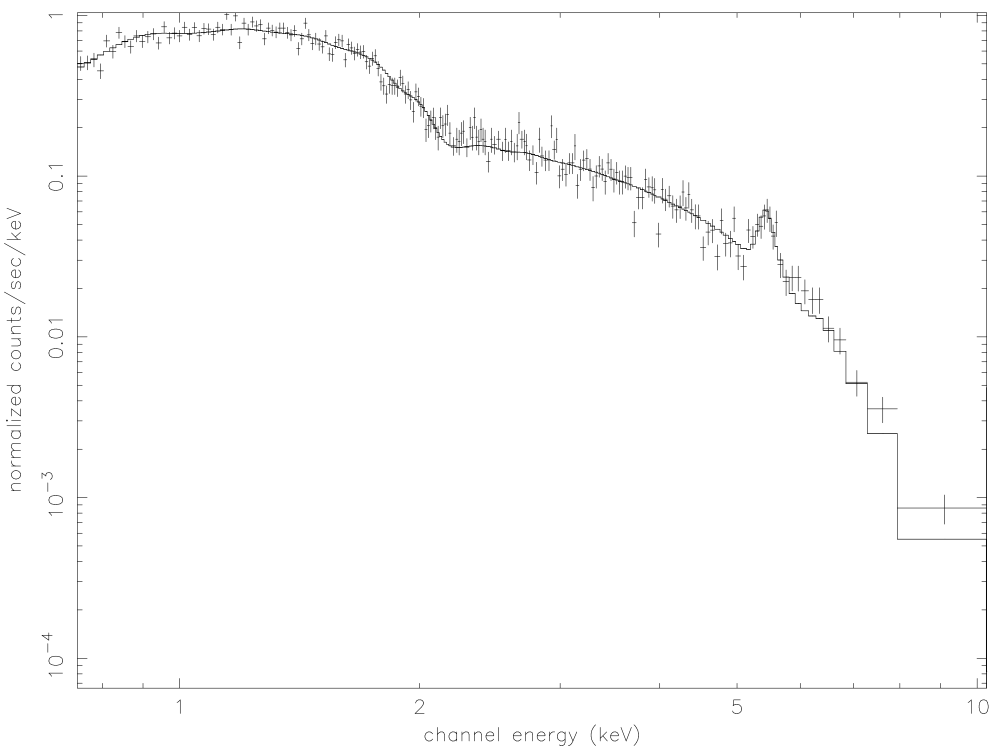

Fig. 5.— CHANDRA ACIS I spectrum of the central 15 arcsec radius region of the cluster RXCJ1504.1-0248. The well visible Fe line allows to confirm the redshift and to measure the Fe abundance.

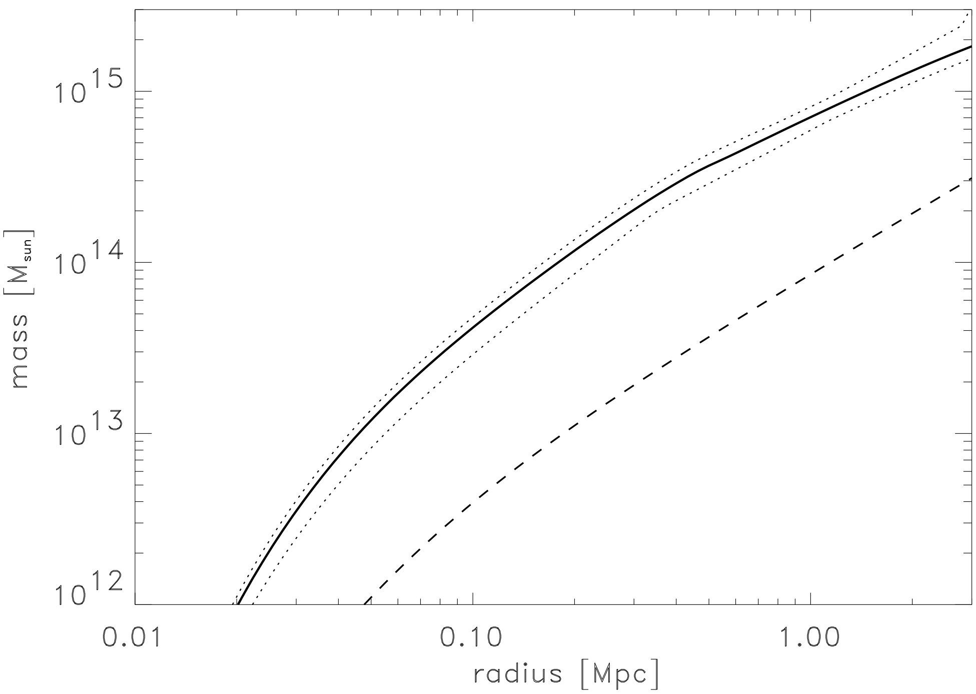

Fig. 6.— Gravitational mass profile of RXCJ1504.1-0248 calculated for the three bracketing gas temperature profiles adopting a Λ-cosmological model with a Hubble constant of $H_0 = 70$ km s^{-1} Mpc^{-1}. The two dotted lines indicate the uncertainties determined from the local minima and maxima in the mass profiles from the three analytic fits to the temperature profile and their scaling uncertainties (see text). Also shown as dashed line is the gas mass profile calculated from the β-model.

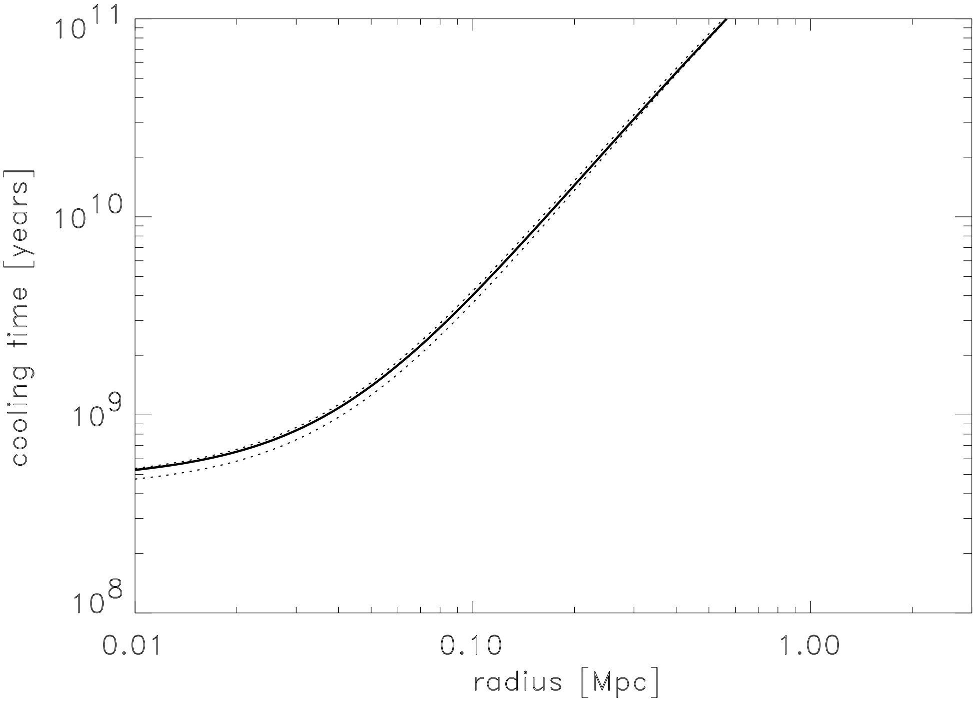

Fig. 7.— Cooling time profile for the ICM in RXCJ1504.1-0248 calculated for the three bracketing gas temperature profiles adopting an Einstein-de Sitter cosmological model with a Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1}.

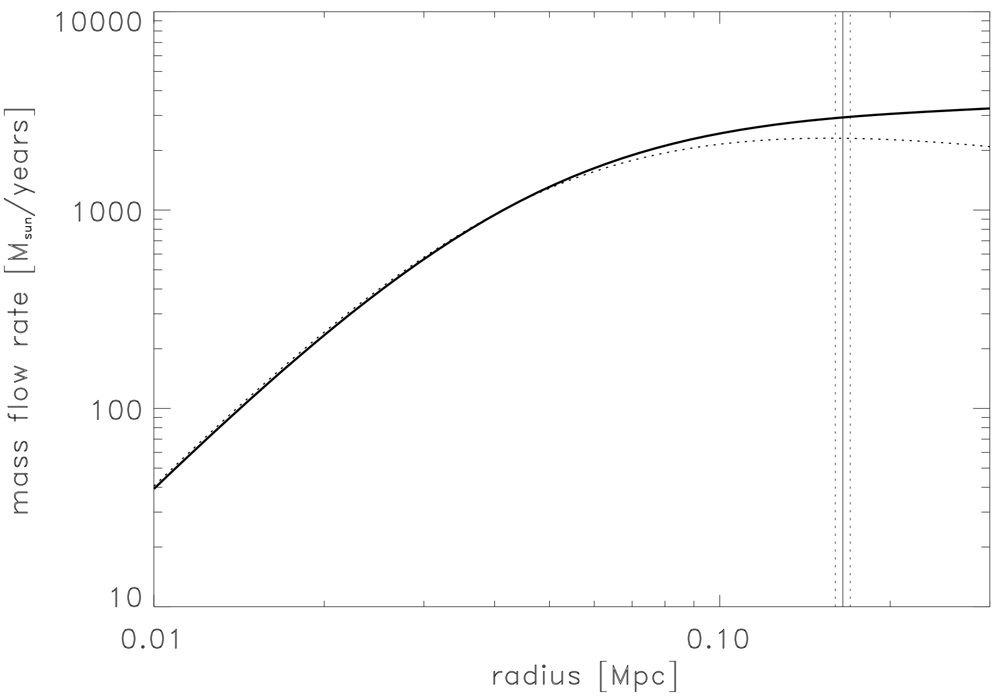

Fig. 8.— Inferred mass flow rates assuming a conventional cooling flow model (solid line = model A; dashed line = model B including gravitational energy gain) as a function of radius for an Einstein-de Sitter cosmological model with a Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1}. The vertical lines indicated the radius with a cooling time of 10^{10} years and its uncertainty.

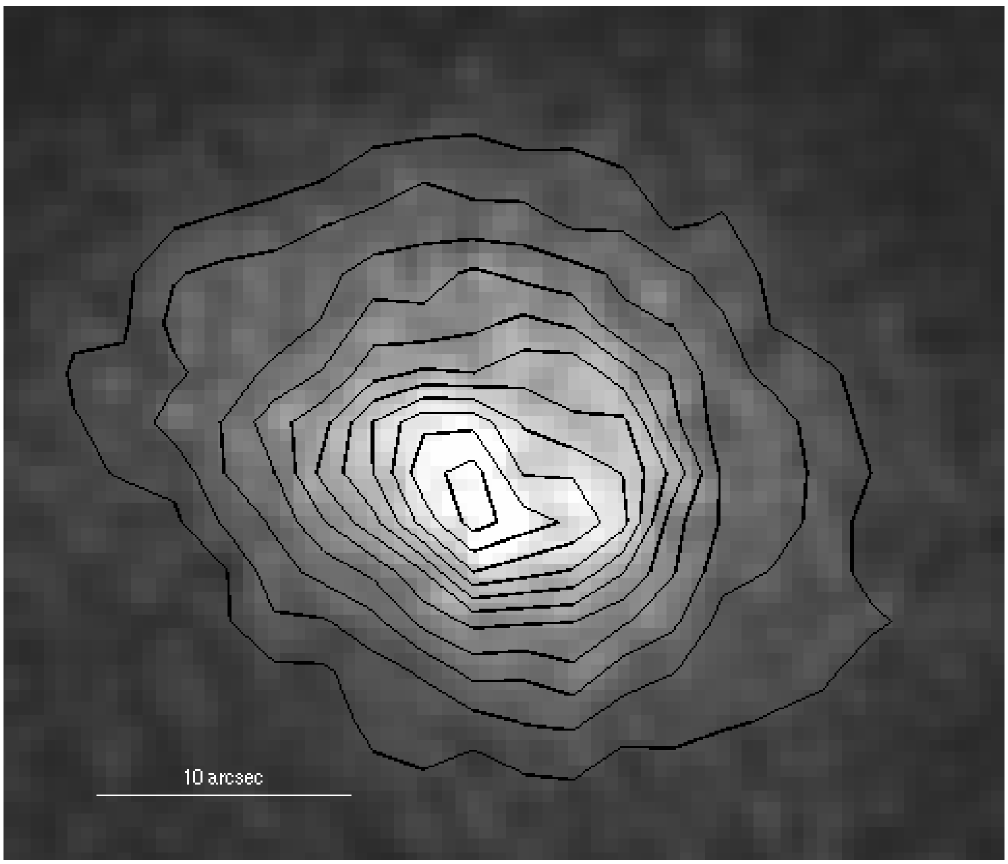

Fig. 9.— Zoomed ACIS I image of the central region of RXCJ1504.1-0248. Some asymmetric distortion is visible NW from the center which may be an indication of possible interaction effects of the central AGN with the cluster ICM. North is up and East is left.

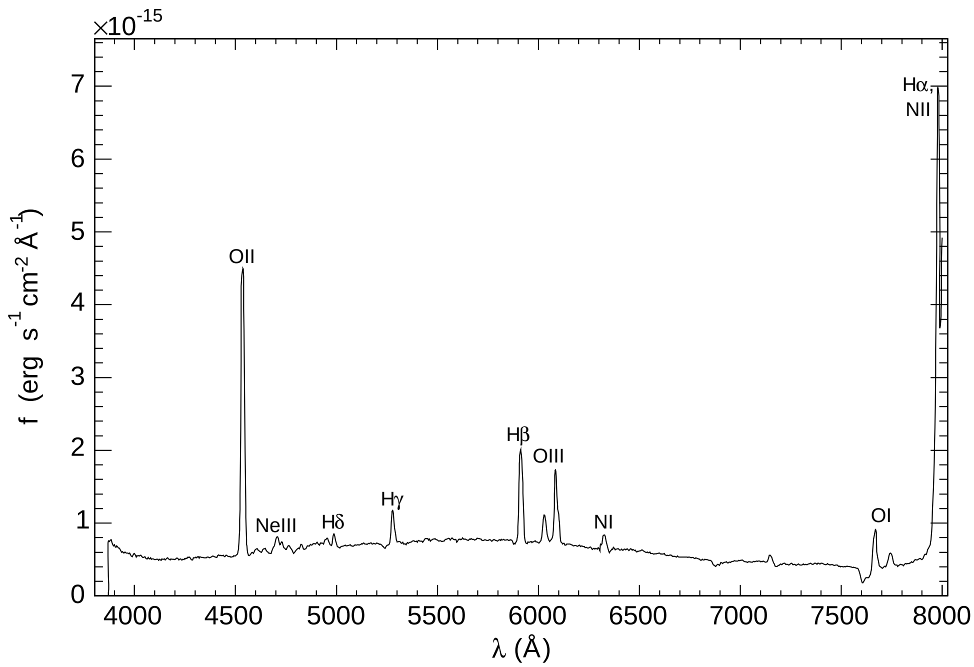

Fig. 10.— Spectrum of the central galaxy of RXCJ1504.1-0248 obtained with the ESO 3.6m telescope. The spectrum has LINER like characteristics quite typical for galaxies in the centers of cooling flows. The spectrum was obtained with the EFOSC2 instrument with a spectral slit width of 2 arcsec positioned through the central part of the galaxy LCRS B150131.5-023636.